REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 14 April 1997	3. REPORT TYPE AND DATES COVERED Final Technical Report

4. TITLE AND SUBTITLE

Fundamental of Acoustic Instabilities in Liquid-Propellant Rockets

5. FUNDING NUMBERS

F49620-94-1-0166

6. AUTHOR(S)

F.A. Williams

AFOSR-TR-97

0355

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093-0411

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NA
110 Duncan Avenue, Suite B115
Bolling AFB DC 20332-0001

10. SPONSORING MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this research was to improve understanding of the mechanisms by which flow, mixing and combustion processes are coupled to acoustic fields in liquid-propellant rocket motors. Particular attention was focused on analyses of amplification mechanisms coupled with finite-rate chemical reactions by use of numerical and analytical methods. A theoretical explanation of empirical correlation of instability boundaries for engine-test results for LOX/RP-1 rockets was developed on the basis of amplification by finite-rate chemical reactions in strained mixing layers. In addition, a new numerical computation of nonlinear amplification mechanisms in LOX/GH_2 combustion suggested a possible explanation of threshold phenomena found in liquid-propellant rockets.

14. SUBJECT TERMS combustion instability, rocket combustion	15. NUMBER OF PAGES 10
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

Fundamentals of Acoustic Instabilities in Liquid Propellant Rockets
Final Report

1. Introduction

This final technical report concerns research performed over a three-year period ending February 14, 1997.

Researchers who participated in the work, in addition to the author, were Dr. Jong-Soo Kim, Professor Paul Clavin and Mr. Chae-Hoon Sohn. Professor Clavin was concerned, in particular, with turbulence and noise effects on combustion instabilities. Mr. Sohn was concerned, in particular, with droplet combustion as an amplification mechanism, especially LOX droplets in gaseous hydrogen atmospheres. Dr. Kim and the author were involved in all aspects of the work, including those of Professor Clavin and Mr. Sohn. The following sections summarize all of this research.

2. Publications

All of this work is now published in the open scientific literature. References [1] through [6] list these publications. The reader is referred to these publications for details of the research. The following sections therefore merely provide summaries of the research.

3. Theoretical Explanation of Acoustic Instability Boundaries

It has been known for some time that the most severe instabilities in liquid rockets are acoustic, that is, sound waves may be amplified by interactions with combustion processes to an intensity high enough to damage the engine. However, the acoustic instability mechanisms have been poorly understood, so that as a design guideline engineers had to rely on empirical methodologies based on previous engine-test results to estimate where the boundaries of acoustic instability lie. Good understanding of the mechanisms by which such empirical relations emerge could help in the design of stable liquid rocket engines without excessive trial and error. One such empirical result is the Hewitt stability correlation. Figure 1 shows the correlation for rocket engines using LOX/RP-1 propellant combinations and like-on-like impinging-jet injectors, in terms of the highest sustainable acoustic frequency and the injection parameter d_o/U_i, where d_o is the orifice diameter of the injector and U_i is the injection velocity.

Here, we are concerned with identification of the instability mechanism that is responsible for the emergence of the Hewitt correlation. We have shown that such mechanisms are relevant even in the presence of turbulence and spatial nonhomogeneities [1]. In the first attempt to identify the main acoustic instability mechanisms, the response

characteristics of various combustion processes have been analyzed to calculate their amplitude and phase relationships with the imposed acoustic waves. Among these processes, the dominant amplification effect is found to be associated with near-extinction diffusion flamelets because the dominant nonlinear term in combustion processes arises from the finite-rate chemical reaction. The time-dependent characteristics of near-extinction flamelets have been analyzed for the strained diffusion flame model by employing activation-energy asymptotics to predict the linear response of the burning rate [2, 3]. These near-extinction strained diffusion flames are expected to be encountered most often between impinging spray fans of fuel and oxidizer. The high sensitivity near extinction can be seen from the well-known S-curve behavior; Fig. 2, obtained from a calculation performed in a counterflow diffusion flame [2], shows a typical result of the steady-reaction-sheet response as a function of the Damköhler number Da. It is clear from Fig. 2 that, for the same fractional variation of Damköhler number, $\delta Da/Da$, shown by vertical bars, the near-extinction flame experiences a much larger reaction-sheet displacement, and flame-temperature variation, as marked by horizontal bars, also is much larger. In addition, the flame responses are expected to diminish as the acoustic frequency becomes greater than the strain rate, since accumulation of the unsteady effect coming from the imposed acoustic oscillations gives rise to the response delay and attenuation effects. More detailed results on the flame responses with acoustic waves are discussed in our published works [2, 3, 4].

In liquid-propellant rocket chambers, the rate of strain decays in the axial direction. Consequently, flamelets near extinction may be expected to be encountered more often in the near-injector region and the dominant amplification effect is considered to be coming from these flamelets near the injectors. This is consistent with observations in engine tests, indicating that stability is often achieved by moving the flame zone away from the injector assembly. The effects of finite-rate chemistry are also consistent with the temperature-ramping test, a stability-rating method in which the fuel is gradually heated until instability begins to disappear. As the temperature of the reactants increases, equilibrium chemistry becomes more prevailing, and the consequent reduction of the amplification contributions results in stable operation of the rocket engine.

The strain rates for these flamelets can be approximated as U_i/d_o, which is the strain rate at the impact point of the two jets and also is the reciprocal of the injection parameter [5]. Since the strain rate in impinging-jet flows tends to be spatially uniform, the value of U_i/d_o represents the strain rate for flamelets in a relatively wide region near the injector. However, the strain rate is expected to fluctuate about U_i/d_o because of turbulence. As the strain rate U_i/d_o is increased by increasing U_i or by decreasing d_o, the chance to encounter

near-extinction flamelets also increases, thereby resulting in a larger amplification rate. This instability tendency is consistent with the Hewitt correlation in that instability appears by decreasing the injection parameter, *i.e.* increasing the strain rate. In addition, the existence of a high-frequency cutoff is suggested because the flame response rapidly decreases with increasing acoustic frequency. A substantial increase of the flame response is seen in our previous analysis if the nondimensional acoustic frequency ω is smaller than a value that is typically less than unity. Therefore, the cutoff frequency should be linearly proportional to the strain rate U_f/d_o, which is again consistent with the Hewitt correlation. Although it is of course necessary to balance amplification against attenuation, and many different phenomena arise, it is interesting that this one particular phenomenon exhibits all of the right functional dependences [5].

4. Nonlinear Acoustic Response of LOX/GH_2 Flames

In the previous year's summary, some of the results on the linear acoustic responses of subcritical LOX/GH_2 droplet flames, obtained by activation-energy asymptotics, were reported. That analysis has now been extended to include the effects of detailed H_2-O_2 chemistry and nonlinear acoustic perturbations. Since the pressure is well below the critical pressure of oxygen, the characteristic time for droplet regression is much greater than the characteristic diffusion time, so that the quasisteady droplet combustion model is still valid, and acoustic pressure oscillations can be superposed on the quasisteady droplet flames. Also, spatial variations of the acoustic wave are not considered because the characteristic length of acoustic waves is much larger than that of droplet flames.

First, the steady-state characteristics of the droplet flames are calculated for various pressures by using an inverse numerical method, in which the flame structures are calculated as a function of the maximum temperature instead of the droplet diameter. Since the flame structure is a single-valued function in the parameter space of the maximum temperature, the inverse numerical method enables us to calculate the flame structure even beyond extinction conditions, where the conventional flame codes fail to converge because of intrinsic flame instability. Therefore, the inverse numerical method provides the flame structures near extinction, with a greater accuracy, where the flame response is expected to be the greatest. Initial results of the steady numerical analysis are shown in Fig. 3, where variations of the maximum flame temperature with the droplet diameter are shown for various subcritical pressures. The extinction droplet diameter is seen to increase with decreasing chamber pressure, and extinction can be achieved for a droplet flame by sufficiently reducing the chamber pressure. Therefore, the numerical results imply that, for

a droplet flame with a given diameter, finite-rate chemistry is more important for low pressures, while equilibrium chemistry prevails for high pressures.

Nonlinear response to the imposed acoustic pressure oscillation $P' = P_a \sin(2\pi t/\tau)$, with the acoustic period $\tau = 10^{-3}$s, is considered for a droplet flame of 2.5 μm-LOX-diameter at the mean pressure $P_m = 10$ atm. The burning-rate fluctuation is nondimensionalized as

$$Q = \int_0^\tau \left(\frac{h}{h_m} - 1 \right) \sin\left(\frac{2\pi t}{\tau} \right) dt$$

where h is the instantaneous rate of heat release and h_m the mean rate of heat release. The variation of Q with the normalized acoustic amplitude P_a/P_m is shown in Fig. 4. The characteristics of the heat-release response are seen to be extremely nonlinear in that the increase of Q with increasing P_a becomes greater as P_a increases and in that the value of Q becomes zero beyond a critical value of the acoustic pressure amplitude P_e. These behaviors can be easily explained from the steady flame structure shown in Fig. 3. Since higher flame sensitivity comes from the effect of finite-rate chemistry, a greater nonlinear heat-release response occurs when the instantaneous pressure is near the minimum. As the acoustic amplitude increases, the flame becomes closer to extinction during the passage of the minimum pressure. Consequently, the increase of Q is faster than the increase of P_a. If P_a is greater than a critical value, which is about 4.9 atm for this calculation, then the chemical reaction during the minimum pressure is too weak to support the flame, so that the flame becomes extinguished and the flame response vanishes.

This type of nonlinear flame response is viewed as a possible mechanism to produce the threshold phenomena discussed in our published work [6], in which acoustic instabilities can be triggered only by acoustic perturbations with amplitudes greater than a critical perturbation amplitude. To show this possibility, three different damping response lines, each corresponding to strong, weak and intermediate damping, are drawn as dashed lines in Fig. 4. Stationary amplitudes of acoustic waves can be found from some of the intersections of the amplification and damping lines, at which the effects of damping and amplification can balance each other. First considering the case of strong damping, the situation marked stable in Fig. 4, the only intersection occurs at $P_a = 0$, so that any acoustic perturbations will be attenuated and the system is stable. For the case of weak damping, there are intersections at $P_a = P_e$ and at $P_a = 0$, and only the intersection at $P_a = P_e$ is stable. Therefore, all acoustic disturbance will eventually converge to $P_a = P_e$, and the system is always unstable. The third case corresponds to intermediate damping, in which two stable intersections at $P_a = P_e$ and $P_a = 0$ are separated by an unstable one at $P_a = P_t$. If an initial

amplitude of disturbance is greater than P_t, the acoustic amplitude will converge to P_e. Otherwise, the disturbances will be attenuated. Consequently, the system is metastable and exhibits threshold behavior. Our analysis has demonstrated that such a metastable acoustic system can exhibit bimodal distributions for the amplitude of acoustic waves. It is also worthy of note that, though the nonlinear response shown in Fig. 4 is calculated from a droplet-flame model, such response behaviors are expected from any type of flame configurations exhibiting usual high sensitivity near extinction.

5. CONCLUSIONS

This work, in total, has identified a particular nonlinear mechanism involving finite-rate chemistry and potential ignition and extinction phenomena that can lead to enhanced amplification as well as nonlinear threshold effects in acoustic instability of liquid-propellant rockets. It is worthwhile to keep this new phenomenon in mind when trouble-shooting instability problems and when designing motors for stable operation. Chemical rockets do involve finite-rate chemistry, which is best not overlooked in addressing engine designs.

6. REFERENCES

1. Kim, J.S., "Effects of Turbulence on Linear Acoustic Instability: Spatial Inhomogeneity," *Liquid Propellant Rocket Combustion Instability* (V. Yang Ed.), *Progress in Astronautics and Aeronautics*, **169**, 431-454, AIAA, Washington DC, (1995).

2. Kim, J.S., and Williams, F.A., "Contribution of Strained Diffusion Flames to Acoustic Pressure Response," *Combustion and Flame*, **98**, 279-299 (1994).

3. Im, H.G., Law, C.K., Kim, J.S., and Williams, F.A., "Response of Counterflow Diffusion Flames to Oscillating Strain Rates," *Combustion and Flame*, **100**, 21-30 (1995).

4. Sohn, C.H. Chung, S.H., Kim, J.S., and Williams, F.A., "Acoustic Response of Droplet Flames to Pressure Oscillations," *AIAA Journal*, **34**, 1847-1854 (1996).

5. Kim, J.S., and Williams, F.A., "Acoustic-Instability Boundaries in Liquid-Propellant Rockets: Theoretical Explanation of Empirical Correlation," *Journal of Propulsion and Power*, **12**, 621-624 (1996).

6. Clavin, P., Kim, J.S., and Williams, F.A., ""Turbulence-Induced Noise Effects on High-Frequency Combustion Instabilities," *Combustion Science and Technology*, **96**, 61-84 (1994).

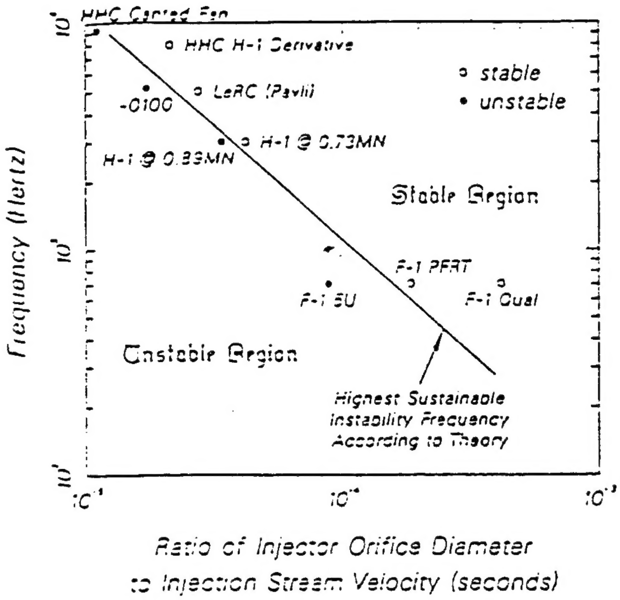

Figure 1. The Hewitt stability correlation for rocket engines using LOX/RP-1 and like-on-like injectors.

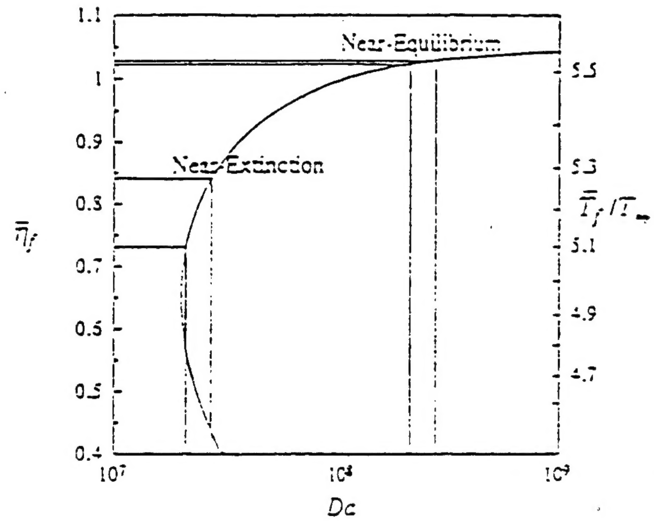

Figure 2. Steady reaction-sheet location and flame temperature as a function of the Damköhler number, showing the high sensitivity of the flame response near extinction.

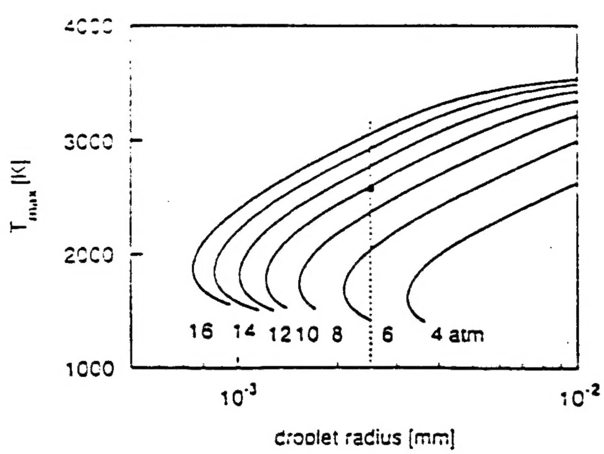

Figure 3. Variation of the maximum temperature with the droplet diameter for LOX/GH$_2$ droplet flames at various pressures.

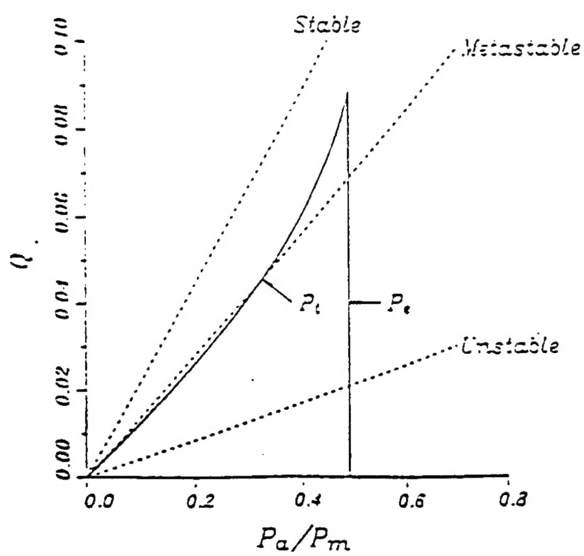

Figure 4. Variation of the nonlinear heat-release response with the normalized acoustic-pressure amplitude. Interaction with intermediate damping exhibits metastable characteristics.